Commentary on "The Theory of the Fluctuations in Brightness of the Milky Way. V" by S. Chandrasekhar and G. Munch (1952)

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ABSTRACT

The series of papers by Chandrasekhar and Munch in the 1950s were concerned with the use of statistical models to infer the properties of interstellar clouds based on the observed spatial brightness fluctuations of the Milky Way. The present paper summarizes the subsequent influence of this work, concentrating on the departure from their earlier discrete cloud model to a continuous stochastic model in Paper V of the series. The contrast between the two models anticipated and parallels current tensions in the interpretation of interstellar structure, as well as intergalactic Lyman alpha clouds. The case of interstellar structure is discussed in some detail. Implications concerning the reification of models and the ability of scientific abstraction to model complex phenomena are also briefly discussed.

To present-day astrophysicists studying the spatial structure of the interstellar medium, the intergalactic medium, or the large-scale distribution of galaxies in the universe, a methodology involving the comparison of the spatial statistics of a model with the observed statistics seems standard. But in fact this approach to interstellar structure, and the models employed, trace back to the work of Ambartzumium in the 1940s (see Ambartzumian 1950 and Kaplan & Pikelner 1970, p.173), and were developed most extensively in a series of papers by Chandrasekhar and Munch in the 1950s (hereinafter CM, Papers I through V). These papers and their results were influential in a number of subsequent works. For example, the relation between the two-point spatial correlation function of galaxies and the angular correlation function, which played a dominant role in the study of large-scale structure in the 1970s and 1980s (before the availability of large redshift surveys and the recognition of the need for additional structure descriptors), involves an equation derived by Limber (1953a, see Peebles 1993, pp.216-217) and inspired by the formulation of CM's 1952 Paper V. For the interstellar medium, several studies of interstellar reddening and HI emission and absorption have been used, assuming a discrete cloud model, to infer the mean number of clouds per unit length along a line of sight and the mean extinction per cloud, based on results given in the CM papers (e.g. Knude 1979). Perhaps the most significant aspect of this early work, however, is the manner in which the rather radical departure from their earlier discrete cloud model to a continuous stochastic model in Paper V parallels current tensions in the interpretation of both the interstellar medium and even intergalactic Lyman alpha clouds, as explained below.

Prior to their 1952 paper, CM presented four papers that were concerned with inferring a few basic properties of a discrete cloud model from the observed spatial fluctuations in the brightness of the Milky Way. The brightness fluctuations were interpreted as being due primarily to the varying number of discrete absorbing clouds along a line of sight. These papers are mathematically daunting, but the basic ideas are simple and have direct relevance today. In Paper I CM derived an integro-differential equation for the brightness fluctuations in terms of the frequency distribution of cloud extinctions. This equation can be seen as a specific example of the Chapman-Kolmogorov equation describing the probability distribution of variables that undergo both continuous changes

as well as "jumps." (A simpler approximate derivation can be found in Kaplan & Pikelner 1970.) In subsequent papers, they solved this equation for the cases in which the system of clouds has infinite extent and a particular distribution of extinction (Paper II), the case of finite extent but constant extinction per cloud (Paper III), and the general case of arbitrary distributions of extinction for infinite extent (Paper IV). Limber (1953b) generalized to finite extent, while Munch (1955, Paper VI) used the model to estimate the decorrelation length in the Milky Way. All of this work assumed a model in which clouds are discrete entities.

A substantial departure, however, is seen in the fifth, 1952, paper V, in which CM considered replacing the discrete cloud model by a continuous stochastic model for the density field. This continuous model was generalized to finite extent by Ramakrishnan (1954). As CM say in their abstract, the new picture "may be considered as an alternative to (or a refinement of) the current picture, which visualizes the interstellar medium as consisting of a distribution of discrete clouds." Besides presaging the study of structure in terms of spatial statistics defined for a continuous random variable, this paper resonates with current work suggesting that the density distribution of Lyman alpha absorbers at intermediate and large redshift (Bi & Davidson 1997, Croft et al. 1998, Haehnelt et al. 1998) and of cool interstellar gas (e.g. Falgarone 1990 for an observational review, Ballesteros-Paredes et al. 1999 for a theoretical discussion) should be viewed as a continuous, albeit intermittent, density and velocity field rather than as a collection of discrete entities called "clouds." The utility of the discrete cloud model in furnishing quantitative results is not in question. The question is whether the discrete cloud model omits some basic physics that is essential to understanding the evolution of the gas and its ability to form stars and galaxies, or leads to an account of such processes that is simply incorrect at some (possibly severe) level. A useful analogy is to consider geologists trying to understand mountain formation and evolution by studying only the peaks high enough to receive snow at some given time, as though they were separate entities. Could such an approach ever discover the fundamental role of stress-driven "wrinkling" of the Earth's crust in the evolution of mountain ranges?

The assumption by CM of discrete clouds in Papers I-IV reflected the general belief among

astronomers at the time that the apparent discreteness in *velocity* space of the absorption lines seen toward OB stars, catalogued most comprehensively by Adams (1949), reflected a discrete *spatial* structure. Since that time such a correspondence has become "clouded" by evidence that the spectral lines are usually blends of multiple components, and the realization that these velocity features only represent a small fraction of the density structure that later became accessible to observers using a number of other techniques. The observed morphology of interstellar gas and dust is now acknowledged to be much more complex than allowed for by the discrete cloud model, in terms of the geometry of density enhancements, nested hierarchical structure, and connectedness. Other authors have argued against the discrete cloud model on grounds other than morphology. For example, Dickey & Lockman (1990), in their review paper on neutral hydrogen in our Galaxy, discuss "the difficulty of objectively delimiting discrete features in emission surveys" in connection with the discrete cloud model. Falgarone et al. (1992), in a study of small-scale molecular cloud structure, use the modest inferred density contrasts to conclude that "...the overall pictureresembles that of the interstellar medium described in 1952 by Chandrasekhar and Munch as a continuous distribution of density fluctuations of small amplitude at each scale...rather than an ensemble of discrete clouds." There is also substantial evidence that the density and velocity fields are scale-free over a large range of scales (see Elmegreen & Falgarone 1996 and references therein), suggesting a continuous distribution (although a system of discrete clouds with a continuous distribution of sizes or tiny discrete clouds of the same size arranged hierarchically could also explain the observational results). Nevertheless, the effect of sensitivity selection effects and the usually poor extent of spatial sampling has continued to reinforce the prevalent interpretation of observations in terms of a collection of discrete, (usually) spherical, or at least smooth, clouds. Any contour map that is based on less than of order ten thousand spatial resolution elements, and which has a sensitivity limit that omits a significant areal fraction of the region being studied, will appear to be a system of more-or-less spherical discrete clouds. What has changed is only an increase in the number of categories of discrete clouds, such as diffuse, dark, giant molecular, clumps, cores, etc., which usually reflect the distinct observational techniques and resolutions employed more than clear evidence of real category boundaries.

There is another, just as significant, fact that has helped entrench the discrete cloud model: the model is intrinsically easier to visualize and to model theoretically. For example, evolution of structure in the discrete model can be abstracted into a generalized ”coalescence equation,” in which the clouds interact only through collisions, reducing the interstellar medium to a more complex version of the kinetic theory of gases. This model was first treated in some detail by Field & Saslaw (1965), and by a large number of subsequent works (an especially illuminating treatment can be found in Silk & Takahashi 1979). There is little connection to the flows on scales larger than an individual cloud size, or coupling in velocity space, except through collisions. Concerning the origin of the clouds, an even simpler model pictures discrete clouds that continually condense by thermal instability, resulting in a conceptually static two-phase model for the interstellar medium (Field, Goldsmith, & Habing 1969). Even though this model has been generalized to include a hot phase involving supernova explosions, as well as other effects, most notably in the influential paper by McKee & Ostriker (1977), the discreteness assumption for the clouds, and the weak connection to the hydrodynamics, persists.

In contrast, if the discreteness assumption is abandoned, one is left, theoretically, with having to infer statistical properties from the hydrodynamic equations for a turbulent magnetized gas, a problem that defies satisfactory solution, let alone conceptualization, even in studies of laboratory and terrestrial unmagnetized incompressible turbulence. The problem lies in the complex and unpredictable behavior of the nonlinear advection operator in the momentum equation. The problem of empirical description is also made more difficult, since instead of counting objects with various attributes, less intuitive statistical descriptors must be employed. Even conceptually, the connection to the fluid equations makes the picture inherently more dynamic and difficult to visualize. (However the continuous CM 1952 model did not address the dynamics, since they did not consider the available information [Adams 1949] concerning the velocity field. The interpretation of the dynamics in terms of the stochastic model was apparently first treated by Kaplan and by von Hoerner in the 1950s–see Kaplan & Pikelner 1970.) The tension between the complexity of empirical and simulated turbulence, on the one hand, and the many attempts to reduce it to a conceptual model, can be seen as a major theme in the history of the study

of turbulence. It seems very likely that the continuous stochastic variable alternative proposed in CM's 1952 paper was influenced by Chandrasekhar's active involvement in turbulence theory around the same time.

Therefore, while providing the basic conceptual basis for the discrete cloud model for several subsequent generations of astronomers studying reddening, extinction, HI, molecular line, and more recently submillimeter continuum observations, this series of papers culminates by asking whether their own discrete model should be replaced by a tu rbulence-like formulation of the problem of interstellar structure, a question which can be seen as a major theme in contemporary studies of the interstellar medium. Although CM (1952) apparently favored the continuous stochastic approach, they gave virtually no guidance concerning criteria by which this approach could be evaluated relative to the discrete cloud model, except for brief reference to the degree to which the models can match observations (see also Limber 1953b). In fact it is only relatively recently that attention has returned (from the time of Kaplan and von Hoerner in the 1950s) to descriptions in terms of continuous density and velocity fields, using, for example, the correlation function (see Miesch & Bally 1994 and references therein), functions related to wavelet transforms (Langer et al. 1995), and principal component analysis (Heyer & Schloerb 1997). For the most part, however, theoreticians and observers alike treat the interstellar gas as some version of the discrete model, which has its theoretical and visualistic advantages, as outlined above.

Part of the continued attraction of the discrete model is its conceptual simplicity, which is usually seen as a positive value in much astrophysical research and science in general. Yet CM were presciently aware of the negative reification effects which accompany the discrete cloud model: "We wish to emphasizea tendency to argue in circles can be noted in the literature in that confirmation for the *picture* [italics in original] of interstellar matter as occurring in the form of discrete clouds is sought in the data analyzed" (CS 1952, p. 104). Such reification continues to the present day, despite occasional warnings.

The fact that CM did not make an explicit decision between the two models based on either empirical or theoretical considerations can be interpreted as acknowledgement of the utility of

some form of an abstraction, or reduction, of the irregular, dynamic, complex, magnetized, and undeniably continuous, interstellar turbulent flow. Indeed, short of simulations, which cannot be regarded as explanatory theories *per se*, the nature of science seems to require some kind of abstraction to a conceptual model in order to generalize from the particular to the universal. The interesting questions that therefore arise from the series of papers by CM are: 1. What kind of conceptual model can best bridge the gap and how can we avoid reifying the model? 2. Is *any* kind of conceptual model capable of bridging the gap? These questions address issues usually relegated to the philosophy or sociology of science. But it seems clear that they should be of concern to scientists in general, since the first question calls for a new approach to the problem at hand, while the second question challenges the basis of the traditional scientific enterprise in the sense that it questions the idea that complex physical phenomena can be adequately described by universal models. Whether CM recognized these broader implications in their shift from the discrete to the continuous model is of course unknown. Yet the fact that their two models still in effect drive most of the contemporary work in the field of interstellar (and intergalactic) structure and star formation, and that the above questions have not yet been answered in the nearly five decades since their work appeared, underscores the fundamental importance of the CM papers, and provides continued motivation for the many astronomers who are trying to bridge the gap in order to understand the evolution of gas and star formation in galaxies.

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